Atoms and X-Rays.[1]

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Isotopes and Ionisation.

THE idea that all atoms of matter might be built of the same primordial units, that is to say, might differ not in material but only in construction, dates back at least as far as Prout. This philosopher endeavoured more than a century ago to show that atoms of all elements were themselves built of atoms of hydrogen. A little earlier Dalton had postulated, in probably the most important theory in the whole history of chemistry, that atoms of the same element were of equal weight. If both these theories were right, the atomic weights of all elements would be comparable with each other as whole numbers. This the chemists soon found was quite incompatible with experimental evidence. They had to choose between the two theories and chose the one that was untrue. In this they were perfectly right, for it is more important that a scientific theory should be simple than that it should be true.

The point cannot be tested by chemical methods, for these require a vast number of atoms, and so can only yield a mean result. The way in which Dalton's postulate was first attacked and shown to be incorrect was in the province of radioactivity, when Soddy showed that lead which was produced from thorium minerals had a different atomic weight from the lead which was produced from uranium minerals. This meant that substances could exist which had identical chemical properties but different atomic weights; these Soddy called isotopes. This reasoning could not be applied to ordinary elements. For these there is only one conclusive test, which is to compare the weights of individual atoms. It is here that positive rays are of such value, for they are atoms carrying a positive charge and moving with so high a speed that they can be detected by a fluorescent screen or photographic plate.

The first experimental comparison of the weights of individual atoms was made by Sir J. J. Thomson by his "parabola" method, in which the rays are subjected to electric and magnetic fields giving deflexions at right angles to each other. Subjected to this test, many of the elements seemed to obey Dalton's rule, giving single or apparently single parabolic streaks expected from groups of atoms travelling with different velocities but all of the same mass. But results obtained with neon suggested that in this gas the atoms were of two different weights 20 and 22, the accepted atomic weight being 20·20. The accuracy of the parabola method of analysis was not sufficient to prove the point, but this was done by means of the mass-spectrograph. With this instrument, by using electric and magnetic fields giving deflexions at 180° to each other, it is possible to focus the rays and obtain a spectrum dependent on mass alone. By measurements of this mass-spectrum it is possible to compare the weights of atoms to one part in 1000. In this way a satisfactory proof was obtained that neon did consist of two isotopes 20 and 22, which, present in the proportion 9 to 1, give the mean atomic weight 20·2. Chlorine, the chemical atomic weight of which is 35·46, was found to consist of two isotopes, 35 and 37. Many of the elements, such as carbon, oxygen, nitrogen, etc., were found to be "simple," that is, to consist of atoms all of the same weight, but even more were found to be "complex," mixtures of two or more isotopes. Selenium, krypton, cadmium and mercury each have six, tin probably eight, and xenon possibly nine isotopic constituents. In all, fifty-six out of the eighty known non-radioactive elements have been analysed into their constituent isotopes or shown to be simple with the results given in the table.

TABLE OF ELEMENTS AND ISOTOPES.

Elements.	Atomic Number.	Atomic Weight.	Minimum Number of Isotopes.	Mass-numbers of Isotopes in Order of Intensity.
H	1	1·008	1	1
He	2	4·00	1	4
Li	3	6·94	2	7, 6
Be	4	9·02	1	9
B	5	10·82	2	11, 10
C	6	12·00	1	12
N	7	14·01	1	14
O	8	16·00	1	16
F	9	19·00	1	19
Ne	10	20·20	2	20, 22
Na	11	23·00	1	23
Mg	12	24·32	3	24, 25, 26
Al	13	26·96	1	27
Si	14	28·06	3	28, 29, 30
P	15	31·02	1	31
S	16	32·06	1	32
Cl	17	35·46	2	35, 37
A	18	39·88	2	40, 36
K	19	39·10	2	39, 41
Ca	20	40·07	2	40, 44
Sc	21	45·1	1	45
Ti	22	48·1	1	48
V	23	51·0	1	51
Cr	24	52·0	1	52
Mn	25	54·93	1	55
Fe	26	55·84	2	56, 54
Co	27	58·97	1	59
Ni	28	58·68	2	58, 60
Cu	29	63·57	2	63, 65
Zn	30	65·38	4	64, 66, 68, 70
Ga	31	69·72	2	69, 71
Ge	32	72·38	3	74, 72, 70
As	33	74·96	1	75
Se	34	79·2	6	80, 78, 76, 82, 77, 74
Br	35	79·92	2	79, 81
Kr	36	82·92	6	84, 86, 82, 83, 80, 78
Rb	37	85·44	2	85, 87
Sr	38	87·63	2	88, 86
Y	39	88·9	1	89
Zr	40	(91)	3·(4)	90, 94; 92, (96)
Ag	47	107·88	2	107, 109
Cd	48	112·41	6	114, 112, 110, 113, 111, 116
In	49	114·8	1	115
Sn	50	118·70	7·(8)	120, 118, 116, 124, 119, 117, 122, (121)
Sb	51	121·77	2	121, 123
Te	52	127·5	3	128, 130, 126
I	53	126·92	1	127
X	54	130·2	7 (9)	129, 132, 131, 134, 136, 128, 130, (126), (124)
Cs	55	132·81	1	133
Ba	56	137·37	(1)	138
La	57	138·91	1	139
Ce	58	140·25	2	140, 142
Pr	59	140·92	1	141
Nd	60	144·27	3 (4)	142, 144, 146, (145)
Hg	80	200·6	6	202, 200, 199, 198, 201, 204
Bi	83	209·00	1	209

By far the most important result of these measurements is that with the exception of hydrogen, the weights of the atoms of all the elements measured, and therefore almost certainly of all elements, are whole numbers to the accuracy of experiment, namely, about one part in a thousand. Of course, the error expressed in fractions of a unit increases with the weight measured,

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but with the light elements the divergence from whole numbers is extremely small. This generalisation, which is called the *whole number rule*, has removed the only serious obstacle to the electrical theory of matter. It enables us to restate Prout's original hypothesis with the modification that the primordial atoms are of two kinds—protons and electrons, the atoms of positive and negative electricity. The proton is very much smaller and heavier than the electron, actually about 1850 times as heavy. According to the nucleus atom theory which we owe to Sir Ernest Rutherford, all the protons and about half the electrons are packed very close together to form a central positively charged nucleus, round which the remaining electrons circulate, somewhat like planets round a sun. All the spectroscopic and chemical properties of the atom depend on the positive charge on the nucleus, which is the excess of protons over electrons. This is clearly the number of planetary electrons in the neutral atom; it is called the *atomic number* and is actually the number of the element in the periodic classification—1 for H, 2 for He, 3 for Li, and so on. The whole-number weight of the atom, on the other hand, will be the total number of neutral pairs of protons and electrons it contains. This is also the number of protons in its nucleus, and is called the *mass-number* of the atom—1 for H, 4 for He, 6 and 7 for the isotopes of Li, and so on. Atoms are isotopic, that is, belong to the same element, when their nuclei have the same net positive charge, but they may have a different total number of protons, and so different weights.

We picture the atom as consisting of a central nucleus and an outer system of electrons, but when we come to inquire into the dimensions of the electrical particles themselves in relation to the dimensions of the atoms they compose, we are faced with a very surprising result. The protons and electrons are infinitesimal compared with the atom. To convey any direct idea of the numerical relations is almost hopeless, and were we to construct a scale model of the atom as big as the dome of St. Paul's, we should have some difficulty in seeing the electrons, which would be little larger than pin heads, while the protons in the nucleus would escape notice altogether as dust particles invisible to the naked eye. If we represent the nucleus of a helium atom as the size of a pea, its planetary electrons would be about a quarter of a mile away. Experimental evidence leaves us no escape from the conclusion that matter is empty. An atom, even of so heavy an element as lead, is as empty as the solar system and only occupies the spherical space we allot to it by virtue of the rapid and continuous rotation of its outer electrons. Led by the knowledge that under certain conditions these outer electrons could be stripped from the atom, and the nuclei thereby enabled to approach closer to each other, Eddington was able to predict that in certain stars matter could attain a density thousands of times greater than the greatest we know. This prediction has been strikingly verified by recent observations on the companion of Sirius, which at the same time have afforded another signal triumph for Einstein's relativity theory.

We have heard a good deal of loose talk in recent years of "splitting" the atom. Whenever you draw your fountain pen from your pocket you split countless millions of atoms in the sense that you violently tear planetary electrons away from them, by the friction between the ebonite and the cloth. This form of splitting is called ionisation. In it the atom suffers no sort of permanent injury. It simply captures the first electron it can to replace the one it has lost, and after notifying the world at large of its recovery by a wireless signal, it goes on exactly as before. In such a solid as copper, the exchange of electrons from one atom to another can be effected with the greatest freedom, and it is the passage of these loose electrons which constitutes the ordinary electric current. I suspect that the high conductivity of the negative glow, and of flames, is due to an exchange of a somewhat similar kind.

I mentioned the despatch of a wireless signal sent by the atom on repair of its injury. The type of this radiation depends on the extent of the damage done. For superficial effects it is light and radiant heat: for deeper and more violent effects it is X-rays. The displacement of the innermost and most tightly bound electrons gives rise to the hardest X-rays. The tightness of binding depends on the nuclear charge, so that for the emission and absorption of the hardest rays the heaviest elements must be employed. This property of the atom has already been dealt with by Sir Oliver Lodge in his address two years ago. It is to be emphasised that in all such cases we are only concerned with the outer electrons. With the nucleus it is a very different state of affairs. To dislodge any part of this requires violence of an altogether higher order, but if it is done the whole atom is changed, and changed permanently. This is no longer ionisation but transmutation.

TRANSMUTATION OF THE ELEMENTS.

Transmutation of the elements, so long sought by the alchemists, takes place spontaneously in the radioactive atoms, the nuclei of which are unstable and periodically eject helium nuclei and electrons, which are the well-known alpha and beta rays. Several claims of artificial transmutation of elements have been made recently in serious scientific journals. I will deal with the more doubtful ones first. Three years ago it was stated that helium was formed when a tungsten wire was deflagrated by an intense discharge. Sir Ernest Rutherford pointed out the extreme improbability of any disruption of the tungsten nucleus under these conditions, and a careful repetition of the experiments, with greater precautions, proved that he was right. Quite recently a claim has been made that helium has been produced by transmutation in a vacuum tube discharge. If true, this would be the greatest discovery in history, but the detection at the same time of neon, another atmospheric gas, is, to my mind, a very suspicious circumstance, and when these alchemists seriously suggest that success or failure may depend on the use of a particular form of obsolete make and break, my scepticism is increased.

A much more interesting case is that of the liberation of gold from mercury by electric discharge, even in an ordinary mercury vapour lamp. Here similar experimental results have been obtained by several investigators in different parts of the world, and the quantities of gold produced are remarkably large—large enough as we shall see to dissipate the hope, so confidently expressed, that it is formed by transmutation of the mercury atoms owing to the addition of an electron to

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their nuclei. This claim was supported, I confess much to my surprise, by a well-known authority, on the ground that since the nucleus is positively charged, it would be quite easy to fire an electron into it. This is pushing the analogy of the sun and planet system to unjustifiable length. We know that a planet directed towards the sun would actually fall into it, but if every time an electron was directed towards a nucleus it fell into it and was absorbed, how could matter have a permanent existence at all?

We know there must be some mechanism in Nature which prevents such a collapse taking place in this simple manner. Even if we grant the theoretical possibility, there are still fatal practical objections. The addition of an electron to the nucleus of one of the isotopes of mercury will turn it into an atom of gold, but cannot alter its weight appreciably. Now the atomic weight of the so-called artificial gold has been determined by Hönigschmid, and agrees within experimental error with the value 197·2 assigned to ordinary gold. Quite recently, by means of a new and more powerful mass-spectrograph, I have been able to resolve the isotopes of mercury, and so determine its composition, which was previously in some doubt. I find that it consists of 198, 199, 200, 201, 202 and 204. There is no isotope 197 previously suspected. This fact, combined with the atomic weight, makes it quite certain that no transmutation of the kind claimed could produce the gold found. This is ordinary gold which must have been present in the mercury from the start. I understand that this view has now been shown to be right by the failure of the experiment when sufficient care is taken to eliminate all traces of gold from the mercury beforehand.

Unless our views on the structure of nuclei are very wide of the mark, failure in such experiments is inevitable, for the forces employed are ludicrously inadequate to cause disruption. The work of Rutherford, Chadwick, Ellis and others leaves no doubt that just as the dimensions of the nucleus are almost inconceivably small—the radius of that of aluminium is probably less than 4×10^{-13} cm.—so the forces binding together its component parts are gigantic and to be measured in millions of volts. Such forces are not yet available in the laboratory. They are, however, provided, on an atomic scale, in the form of the alpha particles shot out of radioactive atoms, and with these Rutherford has succeeded in producing real and definite transmutation. The method consists in bombarding the atoms with the swiftest alpha particles, which are helium nuclei with a velocity of more than 100,000 miles per sceond, which corresponds to an energy of many millions of volts. In order to effect a disintegration, these projectiles must make a direct hit on the nucleus. When this happens in the case of most elements lighter than potassium, a proton is dislodged from the nucleus, which is thereby transmuted into another element.

These observations have recently been strikingly confirmed by Blackett, who, using the beautiful Wilson fog-track method, has actually succeeded in photographing the disintegration of nitrogen nuclei struck by swift alpha particles. As I have already pointed out, the dimensions of the nucleus are minute compared with those of the atom. It can be calculated that an alpha particle colliding with an atom will only hit the nucleus once in about ten thousand million collisions, so that although each alpha particle makes about 200,000 collisions in completing its track, a very large number of photographs had to be taken. Actually some 400,000 tracks were photographed and eight disintegrations detected. In these the thin track of the dislodged proton could be clearly seen, and a somewhat unexpected feature brought out is that in each case the projectile is retained by the target. The nitrogen nucleus loses one proton but captures the helium nucleus fired at it, and so would appear to become an isotope of oxygen of atomic weight 17. No such body is known in Nature, which suggests that the atom so formed is not permanently stable.

ATOMIC ENERGY.

In the possibility of artificial transmutation lies the hope of one day releasing the so-called "atomic" energy. The whole-number rule is not mathematically exact, and it has been shown by direct measurements on the mass-spectrograph that an atom of helium, which consists of four protons, two nuclear electrons and two planetary electrons, weighs nearly 1 per cent. less than four atoms of hydrogen, each of which consists of one proton and one electron. The number of particles is identical, and the change of mass is ascribed to the different way they are arranged, and is called the packing effect. The theory of relativity tells us that mass and energy are interchangeable, and that if a mass m is destroyed, a quantity of energy equal to mc^2 is produced, where c is the velocity of light. Hence, if we could transmute hydrogen into helium, we should produce energy in quantities which, for any sensible amount of matter, are prodigious beyond the dreams of scientific fiction. For one gram atom of hydrogen, that is the quantity in 9 c.c. of water, the energy is

$$0{\cdot}0077 \times 9 \times 10^{20} = 6{\cdot}93 \times 10^{18} \text{ ergs.}$$

Expressed in terms of heat, this is $1{\cdot}66 \times 10^{11}$ calories, or in terms of work 200,000 kilowatt hours. In a tumbler of water lies enough power to drive the *Mauretania* across the Atlantic and back at full speed.

Here we have at last a supply sufficient even for the demands of astronomers; indeed, there is now little doubt that the vast supply of energy radiated by the stars can be kept up for centuries by the loss of an insignificant fraction of their mass. Whether this process is a degradation of hydrogen into helium, or the complete annihilation of matter by coalescence of its protons and electrons, is at present unknown. How long it will be before man is able to effect transmutation of matter into energy, and to what uses he will put such vast potentialities, are interesting subjects for debate. If scientific knowledge maintains its present rate of progress, the balance of probability is in favour of ultimate success, but this appears so far off that almost any speculation may be permitted. It may be that the operation once started is uncontrollable, and that the new stars which flare out from time to time in the heavens are but an intimation broadcast to the universe, of the first successful large-scale experiment on a far-distant world. It may be that the highest form of life on our planet will one day discover supreme material power, or cataclysmic annihilation, in the same ocean wherein, we are told, its lowest forms originally evolved.

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